Forum for Electromagnetic Research Methods and Application Technologies (FERMAT)

Investigation of X-band Digital High-Power Circulator-Based Phase Shifter

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Abstract: A novel design of X-band digital high-power phase shifter (PS) based on ferrite-circulator is presented. As verification of the presented design, a digital high-power ferrite-circulator-based PS of 180° is designed. Simulated results show that return losses and insertion losses are better than -22.87dB and -0.32dB at center frequency 9.25GHz, respectively. Results also indicate great consistency in both states. A power-handling capacity of 280kW is achieved under vacuum condition, and the switching time is within the level of microsecond. Moreover, the proposed structure is easily fabricated.

Microwave phase shifter (PS) is very important in radar, communication systems. Specially, microwave PSs with high power-handling capacity are of great interest. There are many kinds of phase shifters widely used such as p-i-n diode PSs, mechanical waveguide PSs and ferrite PSs. A p-i-n diode PS has an extremely short response time, and its performance is great under low power-handling capacity [1]. A mechanical waveguide PS is suitable in high-power application but its switching time is dozens of millisecond, and it easily sparks [2]. A ferrite PS is widely used in radar system where high power and reliability in needed, and has a relatively short response time on the order of microseconds [3]. To realize higher power-handling capacity and shorter response time, a novel design of digital high-power PS based on ferrite-circulator for X-band is presented. Finally, a digital high-power ferrite-circulator-based PS of 180° at center frequency 9.25GHz is designed as verification of the presented design.

Keywords:
Digital high-power phase shifter, ferrite-circulator, switching time

Reference:

1. Michael Parnes, and Orest Vendik, “P-i-n diode phase shifter in waveguide structure,” *Microwave And Optical Technology Letters*, vol. 57 , pp. 1666–1671 , July 2015.
2. Chao chang, Letian Guo, Sami G. Tantawi, Yansheng Liu, Jianwei Li, Changhua Chen, and Wenhua Huang, “A new compact high-power microwave phase shifter,” *IEEE Transactions On Microwave Theory And Techniques*, vol.63, pp. 1875–1882, June 2015.
3. A.L.Geiler, J.Wang, I.Viswanathan, S.d.Yoon, J.S.Gao, Y.Chen, et al, “Miniature, tunable, and power efficient ferrite phase shifter devices,” *Aerospace & Electronics*

Conference (NAECON), Proceedings of the IEEE 2009 National, pp. 281–287, July 2009.

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USTC

Investigation of X-band Digital High-Power Circulator-Based Phase Shifter

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Abstract

- A novel design of X-band digital high-power phase shifter (PS) based on ferrite-circulator is presented.
- After giving the theory and design procedure of the PS, a digital high-power ferrite-circulator-based PS of 180° is designed as verification.
- The return loss and insertion loss are better than -22.87dB and -0.32dB at center frequency 9.25GHz. The power-handling capacity is 280kW under vacuum condition.

Keywords—digital high-power PS; ferrite-circulator; switching time.

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1. Introduction

2. Phase shifter scheme

3. Analysis of power capacity

4. Conclusion

Introduction

◆Microwave phase shifter is the key component of phased array.

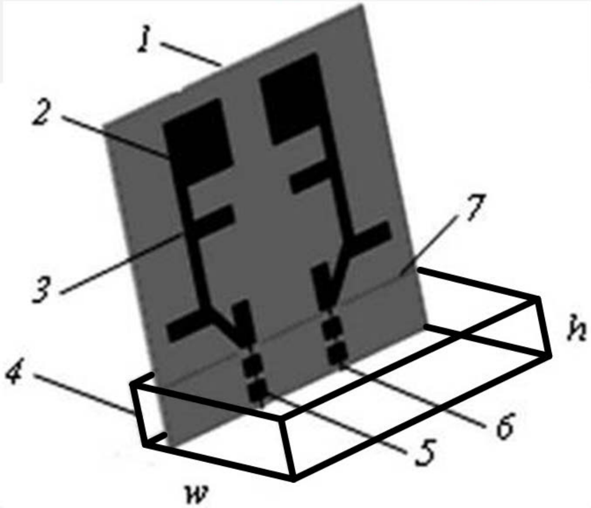
◆High power microwave is required in some applications.

◆ Microwave phase shifters with high power-handling capacity, fast-responding are of great interest.

Introduction

Referenced Works

Lots of phase shifters have been presented in the literatures. Some critical parameters are difficult to meet at the same time, such as fast-responding, high power capacity and low insertion loss.



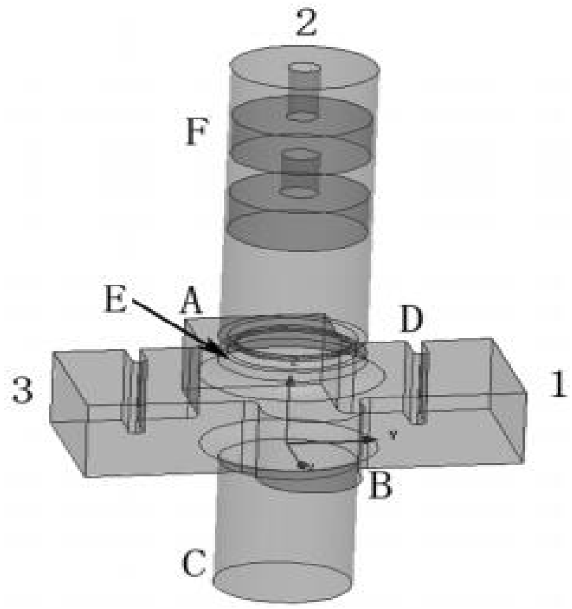
PIN diode phase shifter in waveguide structure

Characteristic:
PIN diode phase shifter in waveguide structure has an extremely short response time, compact structure. But it has a low power-handling capacity because of the limitation of breakdown voltage of the PIN diode

Michael Parnes, and Orest Vendik, “P-i-n diode phase shifter in waveguide structure,” Microwave And Optical Technology Letters, vol. 57 , pp. 1666–1671 , July 2015.

Introduction

Referenced Works



The compact HPM phase shifter

Characteristic:
The compact HPM phase shifter has the advantages of high-power capacity and low loss. But its switching time is dozens of millisecond because a servomotor is used to adjust the output RF phase.

Chao chang, Letian Guo, Sami G. Tantawi, Yansheng Liu, Jianwei Li, Changhua Chen, and Wenhua Huang, “A new compact high-power microwave phase shifter,” IEEE Transactions On Microwave Theory And Techniques, vol.63, pp. 1875–1882, June 2015.

Introduction

Challenges

Realizing phase shift of large angle with low loss

Higher power-handling capacity and shorter response time

Solution

1. Propose a novel structure of switch-type waveguide phase shifter
2. Introduce high-power ferrite circulators as switches

Introduction

Novel Structure

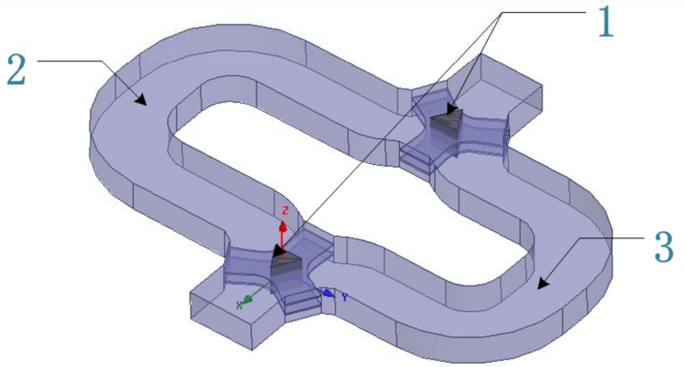
A novel waveguide phase shifter operating at X band, with the following characteristics:

–Low loss

–Shorter response time than mechanical phase shifters

–Higher power capacity than PIN diode phase shifters

- The whole structure consists of three parts.
- Theoretical analysis or design approach is given for each part.



1—High-power ferrite circulators
2—U-type rectangular waveguide2
3—U-type rectangular waveguide1

1. Introduction

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Phase shifter scheme

Basic Schematic Diagram of Phase Shifter

◆Operating principle:

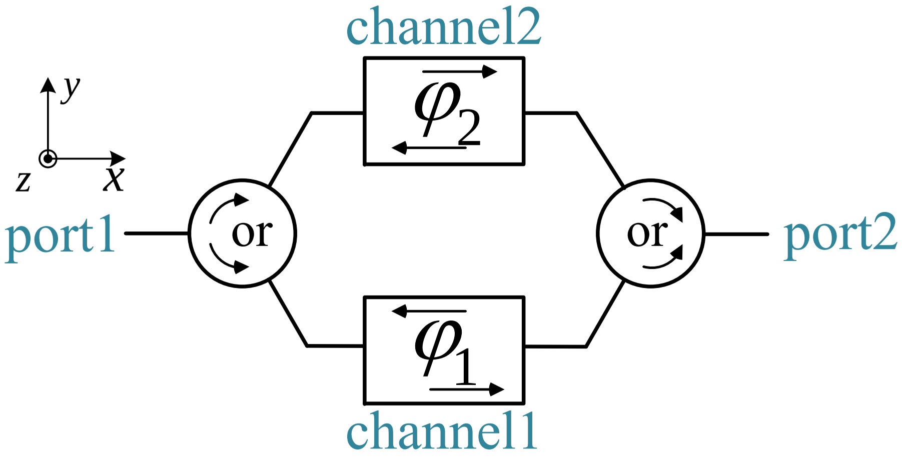
- Signals will transmit from port1 to port2 through the channel1 when the direction of external static magnetic field H_{dc} applied to circulators is –z (state1).
- Signals will transmit from port1 to port2 through the channel2 when the direction H_{dc} is +z (state2).

- Phase shift :

$$\Delta\varphi = \beta L_2 - \beta L_1$$
$$= \varphi_2 - \varphi_2$$

where

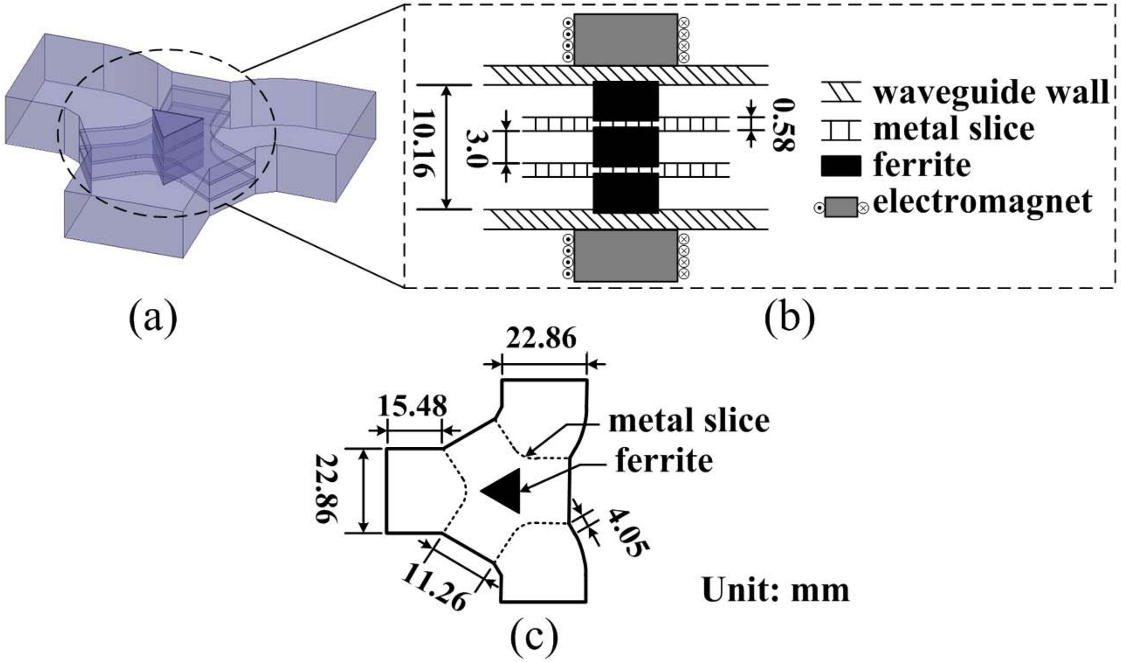
$$\beta = \sqrt{k_0^2 - (\pi/a)^2}$$


channel2
φ_2
y
z
x
port1
or
or
port2
φ_1
channel1

Phase shifter scheme

High-power Ferrite Circulator

The figure gives a high-power ferrite circulator operating at 9.25GHz, which is derived from waveguide Y-junction.


10.16
3.0
0.58
waveguide wall
metal slice
ferrite
electromagnet
(a)
(b)
22.86
15.48
22.86
11.26
4.05
metal slice
ferrite
Unit: mm
(c)

(a) Simulated structure of the circulator; (b) Details of the Y-junction; (c) Top view of the circulator.

Phase shifter scheme

Selection of Ferrite Material

Principles of selecting ferrite material:

- Normalized magnetic moment: $p = \gamma M_s / \omega$
- Normalized magnetic field: $\sigma = \gamma H_{dc} / \omega$
- Damping coefficient: $\alpha = \gamma \Delta H / (2\omega)$

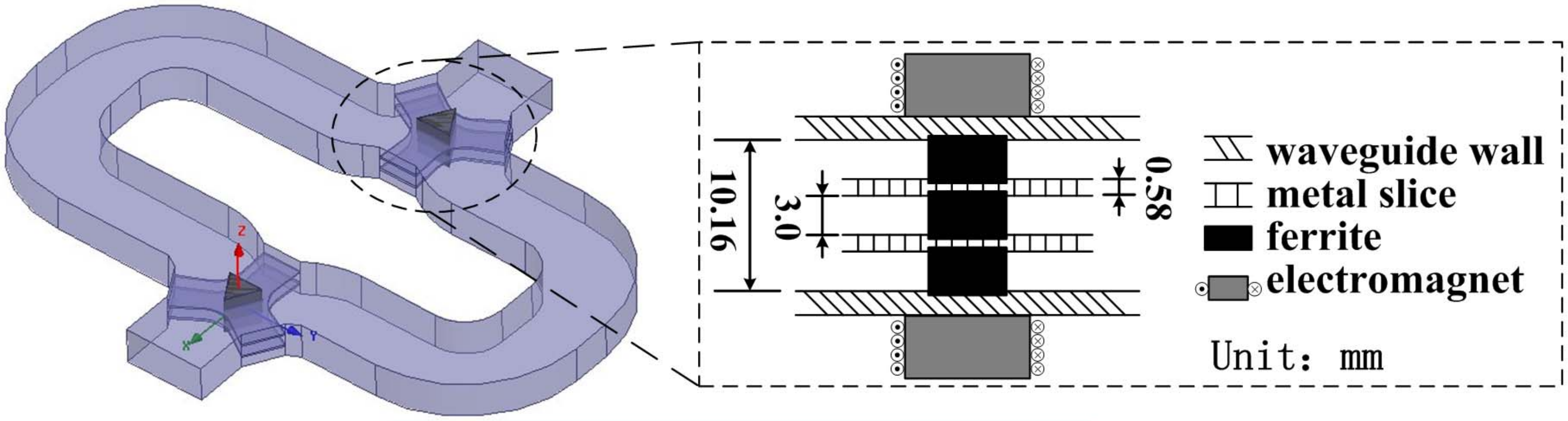
Where γ and ω denote gyromagnetic ratio and operating frequency, respectively. M_s and ΔH are magnetic saturation and resonance line-width of ferrite, respectively.

Considering the performance of high-power capacity and return loss, the ferrite with $\varepsilon_r = 14$, $M_s = 1600/4\pi$ kA/m and $\Delta H = 40/4\pi$ kA/m is selected.

Phase shifter scheme

Configuration of The Phase Shifter

- ◆Electromagnets: ensure the external static magnetic field H_{dc} of about 20 kA/m upon ferrites.
- ◆Metal slices: to keep the temperature of ferrites in the acceptable range and reduce reflections.

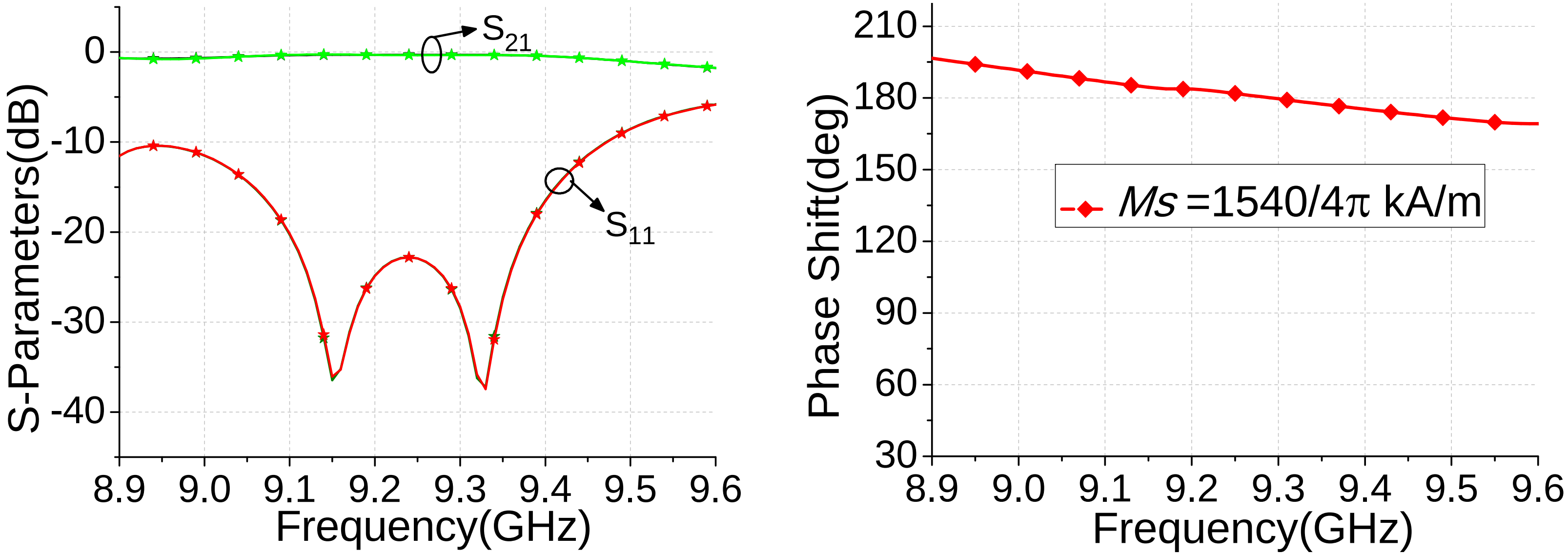

z
y
x
10.16
3.0
0.58
waveguide wall
metal slice
ferrite
electromagnet
Unit: mm

Configuration of the phase shifter

Phase shifter scheme

Performance of S-parameters

◆S-parameters of the proposed phase shifter in state1 and state2



(a) Magnitude

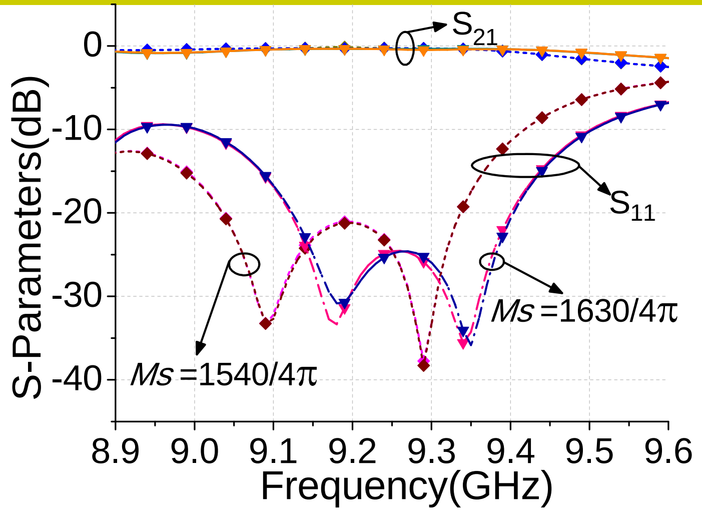
(b) Phase shift

Return losses and insertion losses are better than -20dB and -0.39dB from 9.1GHz to 9.38GHz, respectively; Phase shift is 180.3° at 9.25GHz.

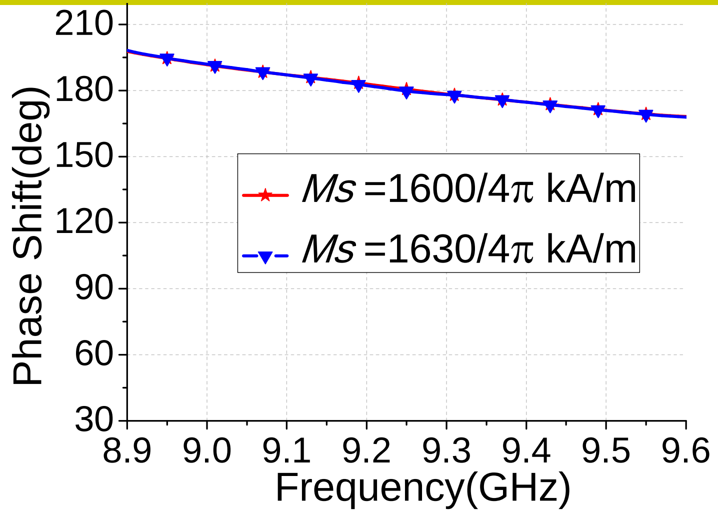
Phase shifter scheme

Performance of S-parameters

- Considering the magnetic saturation of ferrites varies with temperature, M_s from $1540/4\pi$ kA/m to $1630/4\pi$ kA/m is used in the simulation.



(a) Magnitude



(b) Phase shift

The performance is still superb nearby 9.25GHz in different M_s.

Phase shifter scheme

Performance Summary

The performance of the phase shifter is summarized in the following table.

Input	**Rectangular waveguide (TE_{10} mode)**
Outputs	Rectangular waveguide (TE_{10} mode)
Operation frequency	9.25GHz
Insertion loss	0.32dB
Return loss	-22.6dB
Phase shift	180.3°
Dimension of ports	22.86×10.16 mm^2

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Analysis of power capacity

Breakdown Electric Field in Vacuum

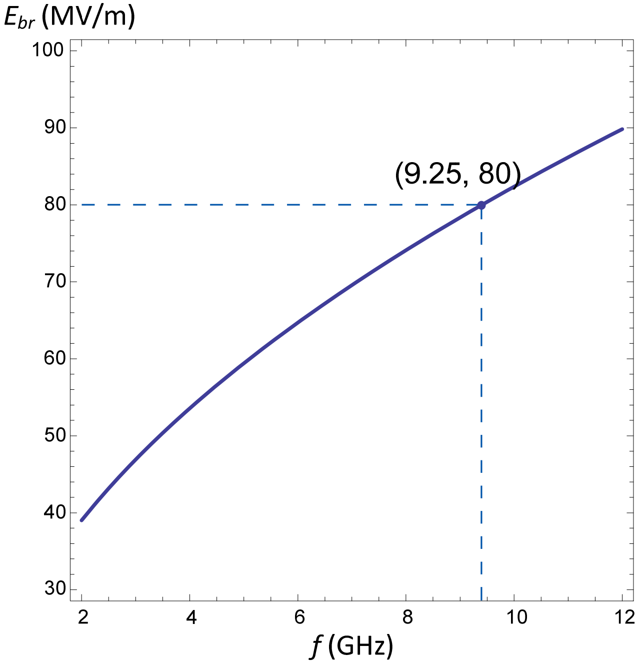
The RF breakdown threshold in vacuum is given by Kilpatrick criterion:

$$f = 1.634\, E_{br}^2\, exp\left(-\frac{8.5}{E_{br}}\right)$$

f： MHz, E_{br}： MV/m

From the figure, we can get:

- The breakdown electric field E_{br} increases with the growth of the frequency f.
- $E_{br} \approx 80$MV/m at 9.25GHz



Kilpatrick limit curve

W.D.Kilpatrick, “Criterion for vacuum sparking designed to include both rf and dc,” Review of Scientific Instruments, vol.28, pp. 824–826, October 1957.

Analysis of power capacity

Breakdown Magnetic Field of Ferrite in the Circulator

The estimation of magnetic field breakdown threshold is as following:

$$h_c = 2\omega\Delta H_k(\omega-\omega_r)/[|\gamma|M_s(\omega/2+\omega_0-|\gamma|M_sN_z)]$$

Where $\omega_0 = |\gamma|H_0$, $\omega_r = \omega_0-(N_z-N_t)\omega_m$, $\omega_m = |\gamma|M_s$, ΔH_k is the ferrite line-width of the k-th spin wave, N_z and N_t is the demagnetization factor in the z direction and transverse direction.

From the estimation formula, we can get:

- The critical value of breakdown magnetic field $h_c$increases with the growth of the ΔH_k.
- $h_c = 24.2$ kA/m when $\Delta H_k = 34/4\pi$ kA/m.

Okada F, Ohwi K, Mori M, “The development of a high power microwave circulator for use in breaking of concrete and rock,” J.Microwave. Power, vol.10, pp. 171–180, 1975.

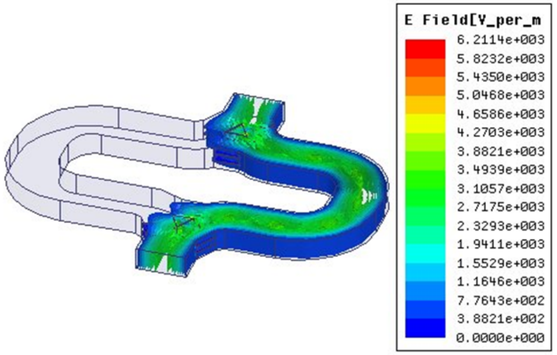
Analysis of power capacity

Calculation of Power Capacity

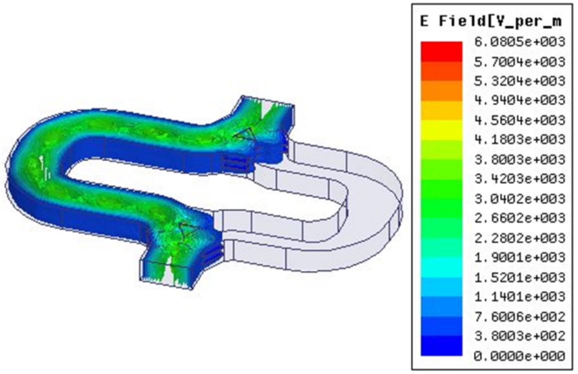
The maximum electric filed E_1 is 6.22 kV/m at 9.25GHz when the input power is 1W.

The power of breakdown electric field is calculated by the following formula:

$$P_e = \left(\frac{E_{br}}{E_1}\right)^2 \cdot P_1 = \left(\frac{80M}{6220}\right)^2 \cdot 1 = 165MW$$



(a) Electric field in state1



(b) Electric field in state2

Analysis of power capacity

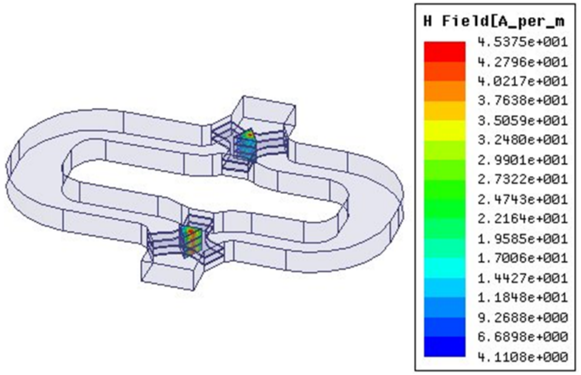
Calculation of Power Capacity

The maximum magnetic filed H_1 in ferrites is 45.2 A/m at 9.25GHz when the input power is 1W.

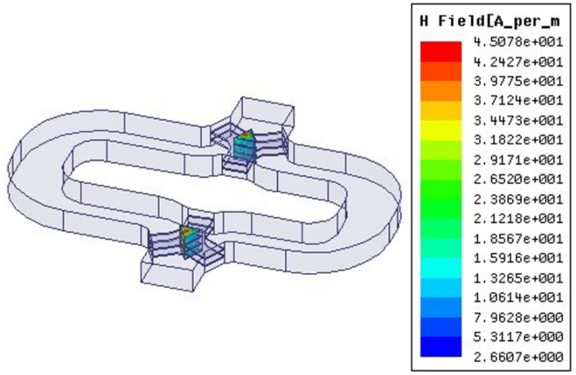
The power of breakdown magnetic field in ferrites is calculated by the following formula:

$$P_h = \left(\frac{h_c}{H_1}\right)^2 = \left[\frac{34000/(4\pi)}{45.2}\right]^2 \approx 280\ \mathrm{kW}$$

The power capacity of the proposed structure is 280 kW


H Field[A_per_m
4.5375e+001
4.2796e+001
4.0217e+001
3.7638e+001
3.5059e+001
3.2480e+001
2.9901e+001
2.7322e+001
2.4743e+001
2.2164e+001
1.9585e+001
1.7006e+001
1.4427e+001
1.1848e+001
9.2688e+000
6.6898e+000
4.1108e+000

(a) Magnetic field in state1


H Field[A_per_m
4.5078e+001
4.2427e+001
3.9775e+001
3.7124e+001
3.4473e+001
3.1822e+001
2.9171e+001
2.6520e+001
2.3869e+001
2.1218e+001
1.8567e+001
1.5916e+001
1.3265e+001
1.0614e+001
7.9628e+000
5.3117e+000
2.6607e+000

(b) Magnetic field in state2

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Conclusion

- An X-band digital high-power circulator-based phase shifter is presented, with short response time, low loss and high power capacity.

- The proposed scheme offers a simple and efficient approach to design digital high-power phase shifters.

- Some basic guidelines to design the high-power phase shifter:
  - Use appropriate waveguide structure to reduce the magnetic field of ferrite material.
  - Use ferrite materials with large ΔH_k while ensuring low loss.
  - Put the bias coil in the place where field intensity is small.